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A HEURISTIC PROCEDURE TO AGGREGATE CONTAINERS ONTO PALLETS AND PLAN THE LOADING OF PALLETS INTO TRUCKS

by

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March 1996

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A HEURISTIC PROCEDURE TO AGGREGATE CONTAINERS ONTO PALLETS AND PLAN THE LOADING OF PALLETS INTO TRUCKS

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Submitted in partial fulfillment
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A heuristic procedure is presented which aggregates containers of multiple products onto pallets and then plans the loading of these pallets into trucks. The efficient loading of products onto pallets and pallets into trucks is an economic fundamental. In 1993 the value of products shipped by truck in the United States exceeded 4.6 trillion dollars or about 75.6 percent of gross domestic product. Industry sources estimate that 98% of all manufactured products are transported on pallets. The heuristic provides feasible solutions to the pallet and truck loading problem in real time. The method considers "real-world" criteria new to the literature, such as stacking compatibility among product containers and axle weight limits for trailers. The procedure is demonstrated with actual examples from the Defense Logistic Agency (DLA) and a commercial company.

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EXECUTIVE SUMMARY

A procedure is presented which aggregates containers of multiple products onto pallets and then plans the loading of these pallets into trucks. Efficient transportation is an economic fundamental: In 1993 the transportation sector of the United States represented 11 percent of total employment, and contributed approximately 14 percent of all federal taxes. At least one third of our national wealth is directly devoted to transportation.

In the United States trucks dominate transportation. In 1993 trucks carried over 65 percent of the total weight shipped and the value of products transported by truck exceeded 4.6 trillion dollars or about 75.6 percent of gross domestic product (GDP). Total cost of transportation by truck was 292 billion dollars or about 5 percent of GDP.

Industry sources estimate that 98 percent of all manufactured products produced in this country are transported on pallets and that 90 percent of the manufactured products transported by trucks use pallets. A pallet is a platform that provides support to the products during transport. A pallet may carry a single product, or a mixture of several products. How should the products be assigned pallets and once assigned how should the products be stacked on each pallet? Damage may occur if heavy products are stacked on top of light products. Products must be compatible with each other to share the same pallet. The characteristics of the products will determine where it may be placed with respect to other products: It may be acceptable for one product to be placed above another but not below it.

How should loaded pallets be placed in the truck? Every truck has a maximum net cargo weight that may legally be carried. Every truck also has an axle weight limit. These weight limits influence the arrangement of pallets in the truck.

Pallets also must be arranged in the truck such that damage during transport is minimized. Heavy pallets should not be placed on top of light pallets. Pallets should be stacked stably so that they do not shift during transport.

Lastly, the ease with which a truck can be loaded and unloaded is a prime concern: Some pallet arrangements will reduce the time required to load and unload the truck. A "good" truck loading keeps pallets with similar products together in the truck.

This paper presents "real-world" criteria that ensure efficient loading of and minimal damage to packaged products during transport by truck. The heuristic is demonstrated with data from the Defense Logistic Agency and a commercial company, providing feasible solutions to the pallet and truck loading problem in real time. This combination of "real-world" criteria with an automated heuristic is new to the literature.

I. INTRODUCTION

A. Transportation and the Economy

Efficient transportation is an economic fundamental. Transportation allows a region to produce the goods it is best suited for, and then trade with other regions the products it produces for the products it needs. In this manner regions utilize resources in the most efficient way, a process Adam Smith [1776] called "geographic division of labor". Without efficient transportation each region would need to divert resources to less efficient local production. Consumers would pay more and consume less. Economies of scale, when production output grows at a faster rate than does raw material input, occur at large production levels. These levels require transport of more raw materials and production equipment.

Transportation is important to the United States economy. In 1993 the transportation sector represented 11 percent of total employment in the United Sates, and contributed approximately 14 percent of all federal taxes and 23 percent of state taxes [Smith, 1994]. At least one third of our national wealth is directly devoted to transportation [Pegrum, 1973].

B. Trucks: The Backbone of American Transportation

In the United States trucks dominate the transportation of goods (Figure 1). In 1993 trucks carried over 65 percent of the total weight shipped and the value of goods transported by truck exceeded 4.6 trillion dollars or about 75.6 percent of gross domestic product (GDP) [Fowler, 1994]. Total cost of transportation by truck was over 292 billion dollars or about 5 percent of GDP.

The role that trucks play in the transportation sector will grow. More than one half of the communities in the country depend entirely on truck transportation to meet their needs [Harper, 1982]. This proportion will increase as railroads abandon lightly used lines. Tom Donahue, president of the American Truckers association, predicts that between now and the turn of the century "30 percent more freight will travel 30 percent farther on 13 percent more trucks" [Dalton, 1994].

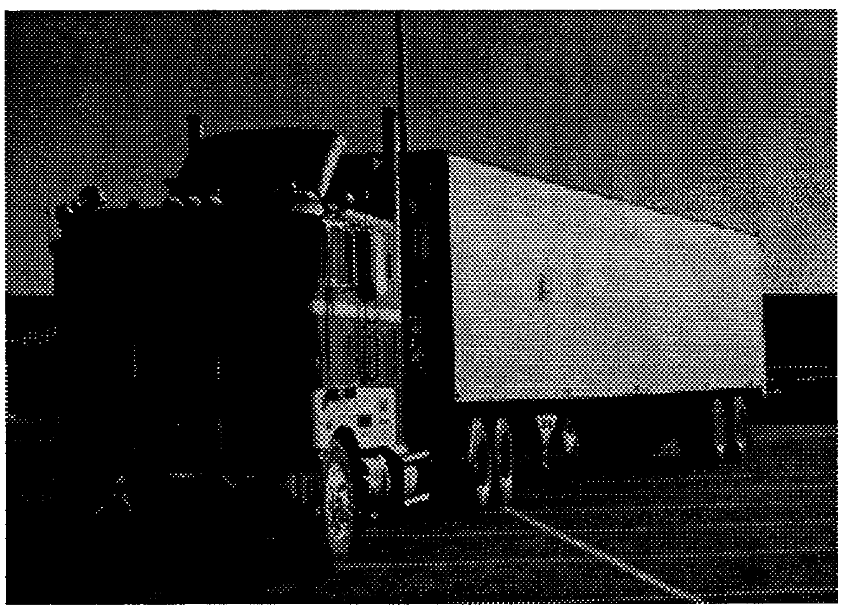


Figure 1. Trucks are the workhorse of American transportation. In 1993 the total weight of goods shipped by truck exceeded 6.5 billion tons with a value exceeding 4.6 trillion dollars or about 75.6 percent of gross domestic product.

C. Pallets

A pallet is a wooden platform that provides a stiff supporting surface and protects items during transport. Items placed on a pallet share this common base and are handled as a single unit, thus saving time. Industry sources estimate that 98% of all manufactured goods produced in this country are transported on pallets [Baker, 1995] and that 90% of the manufactured goods transported by trucks use pallets [Norie, 1995].

II. BACKGROUND

In this section terminology and procedures used in the transport of consumer goods are discussed in two functional areas: Warehouse operations and truck loading operations. Warehouse operations encompass all steps required to prepare consumer goods for transport. Truck loading operations are the steps directly related to placing the prepared consumer goods in a truck.

A. Warehouse Operations

1. Customer Order

The process of transporting finished goods begins with a customer order. The order consists of one or more items identified by stockkeeping unit (SKU), federal stock number (FSN) or some equivalent label. The customer order (Figure 2) shows order quantity of each SKU, and normally includes a product description to provide additional documentation. A commodity class may also be given for each SKU which may influence the cost of transport or the manner in which it is handled.

SKU	Product Description	Order Quantity	Commodity Class
1234	Product A	150	Food
1235	Product B	200	Poison
2357	Product C	15	Food
2578	Product D	75	Food
3590	Product E	400	Food
3998	Product F	125	Cleaner

Figure 2. A customer order specifies the items and quantities required. A Stock keeping unit (SKU), federal stock number (FSN), or some equivalent label will identify each item. It is helpful to have a product description accompanying the SKU for documentation. A commodity class may influence shipping cost or handling.

2. Cardboard Containers

Most SKUs are shipped in rectangular cardboard containers, characterized by their length, width, height and weight (Figure 3). Containers may be rotated but are rarely tipped: The length and width may be exchanged but their height is fixed.

The weight that may be stacked on top of each container is usually specified in terms of a stack height: The maximum permissible number of identical containers which can support themselves vertically.

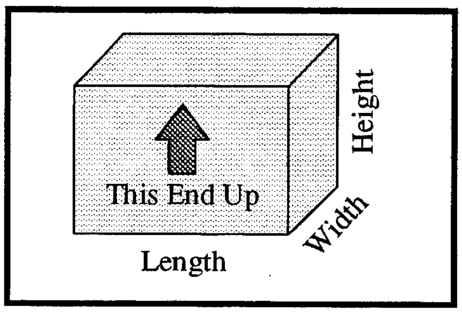


Figure 3. Rectangular containers are used to package SKUs for transport. A container is defined by its length, width, height and weight. A container may be rotated but is rarely tipped: Its lateral dimensions may be exchanged but its height is fixed.

3. Pallets

Cardboard containers are usually stacked on a pallet for transport. Pallet dimensions may vary depending on the item being transported, the type of transportation used, and the needs of the user. In trucking there are primarily two types of pallets used: The standard pallet and the four-way pallet. These two pallets types share a common dimension of 40x48 inches (102 x 122 cm) (Figure 4). Pallet height depends on the weight the pallet will carry and is normally between 1.75-4.75 inches (4.5-12.1 cm) [National Wooden Pallet & Container Association, 1967]. Pallet weight depends on the type of wood used in construction and its moisture content: Normal pallet weight is between 40 and 60 pounds (18-27 Kg). A standard pallet has two slots on its 40-inch side so that it may be lifted by a forklift. It may also be tipped and lifted on the 48-inch side but this is more difficult and time consuming. A four-way pallet has slots on all four sides allowing for easier forklift access.

Figure 4. A wooden pallet is commonly used to support and protect packaged goods during shipment. There are primarily two types of pallets used in trucking: The standard pallet (shown above) and the four-way pallet. Usual dimensions are 40x48 inches(102 x 122 cm). Pallet height is normally between 1.75-4.75 inches. Depending on construction, pallets normally weigh between 40 and 60 pounds (18-27 Kg). Each pallet has two slots on the 40-inch side so that it may be lifted by a forklift. A standard pallet can be tipped and lifted via the 48-inch side, but with more difficulty.

4. Placing Containerized SKUs onto Pallets

Individual containers are placed on a pallet in layers (Figure 5). The lateral dimensions of a layer may be smaller or sometimes a bit larger than the pallet. Containers in a layer may have different dimensions but should share a common height. This common height provides a uniform base for the next layer.

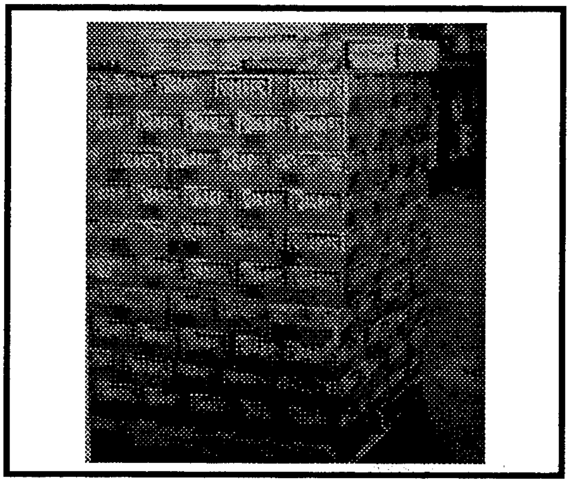


Figure 5. Individual containers are placed on the pallet in layers. The lateral dimensions of a layer may be smaller than the pallet, or sometimes a bit larger. Containers in each layer should share a common height. The full pallet shown has 10 layers.

5. Full Pallets

A "full pallet" is a pallet that contains layers of a single SKU arranged in an efficient manner. For practical purposes most full pallets are about 60 inches (150 cm) tall. This makes handling easier. Full pallets of a given SKU are uniform: They possess a common geometry and SKU quantity. For example, all full pallets of product A would combine containers into layers, and layers into pallets in the same manner and therefore have identical SKU quantities.

SKUs are typically produced in economic order quantity in anticipation of a future demand. They are then stacked as full pallets, shrink-wrapped and stored in the warehouse.

6. Mixed SKU Pallets

When a customer order requires SKU quantities that are not a multiple of the full pallet quantity, mixed SKU pallets may be built. Each layer of the mixed SKU pallet may also contain more than one SKU. A special instance of the mixed SKU pallet is the mixed layer pallet: It contains more than one SKU but each of its layers contain only one SKU (Figure 6).

The decision problem here is: How should SKUs be assigned to pallets and once assigned how should they be placed on the pallet in layers? The process of combining SKUs on a pallet is called pallet picking.

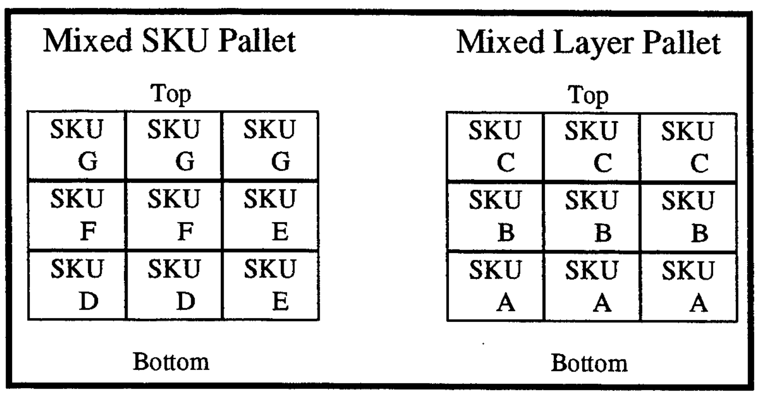


Figure 6. The mixed SKU pallet contains more than one SKU. Each layer of the mixed SKU pallet may contain several different SKUs. The mixed layer pallet is a special type of mixed SKU pallet: Each of its layers consist of only one SKU.

One objective when building a mixed SKU pallet is stability. Stability depends on the characteristics of the individual SKUs as well as the method used to combine SKUs into layers and the layers into mixed SKU pallets [Ram 1992]. Each layer will depend on the layer above and below it for stability [Carpenter and Dowsland, 1985].

If a mixed SKU pallet is stable it may be possible to stack another pallet on top. If a mixed SKU pallet is not stable, topping it with another pallet may cause damage during transport (Figure 7).

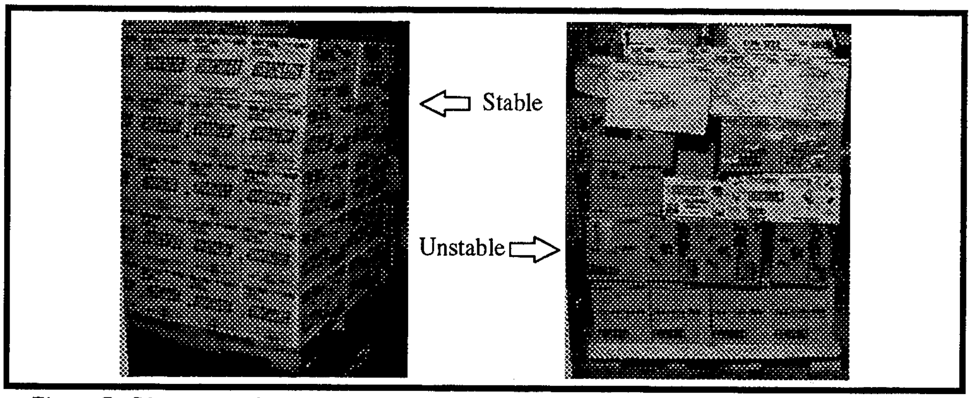


Figure 7. Placement of containers on a pallet is done in such a manner that the entire pallet is stable. If a pallet is stable it is possible to stack another pallet on top of it. If a pallet is not stable containers may shift during transport causing damage. The full pallet on the left is an example of a stable pallet that could support another pallet on top. The mixed SKU pallet on the right is an example of a pallet that is unstable. This pallet provides minimal support for the top layers and could not have another pallet placed on top.

SKUs must be compatible with each other to share the same pallet. For instance, commodity classes food products and poisons should not be commingled. It may be acceptable for one SKU to be placed above another but not below it. For example, it may be acceptable for food products to be placed above household cleaners but unacceptable to reverse this. Additionally, damage may occur if heavy SKUs are placed on top of light SKUs or liquids on top of dry goods (Figure 8). In the context here a SKU that is compatible with another SKU may be placed on top or beside that SKU. For instance, if A is compatible with B, A may be placed on top or beside B. Compatibility is not necessarily symmetric.

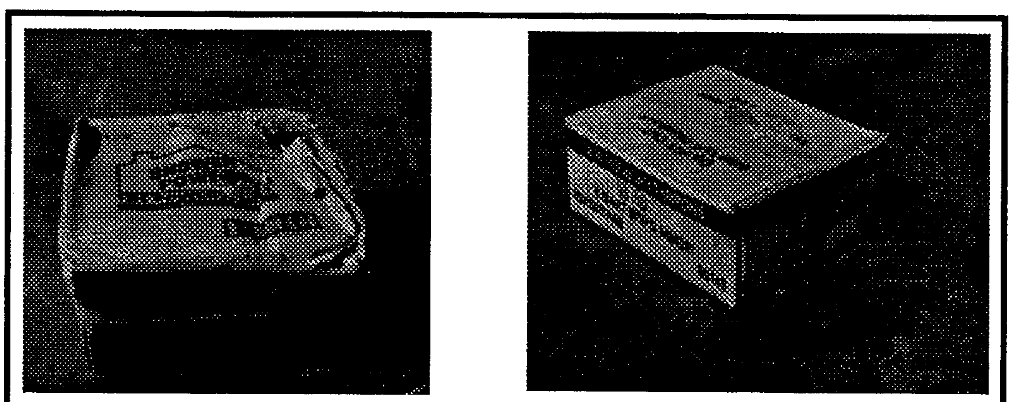


Figure 8. Damage may occur if containers are stacked incorrectly on the pallet. The container on the left was crushed by a heavier container on top of it. The container on the right was damaged by liquid leaking from the container above it.

A mixed SKU pallet should combine SKUs that are located close to each other in the warehouse. This reduces the time required for pallet picking. Additionally, the distance loose containers are carried is reduced thus reducing workload and risk of damage.

7. Warehouse Description

A warehouse is a building, or a part of one, designed for the storage of goods. Normally, the warehouse has specified areas, commonly called bins, reserved for each SKU. Each bin normally contains full pallets, full layers and individual containers of that SKU. The pick order is related to the physical placement of SKUs in the warehouse (Figure 9). Generally, SKUs with similar characteristics are stored together. For instance, SKUs that share a common size cardboard container may be stored in the same area of the warehouse.

The warehouse is the normal point of embarkation for SKUs. Usually, the first step in transporting a SKU is to move it from its bin to a staging area. A staging area is a location in the warehouse where the SKUs that comprise a truckload are gathered prior to being loaded in a truck.

The truck loading dock is the point, usually in the warehouse, that SKUs are placed into the truck. Trucks normally back up to the loading dock. The floor of the loading dock is level with the floor of the truck allowing forklifts to carry the palletized SKUs from the staging area directly into the truck.

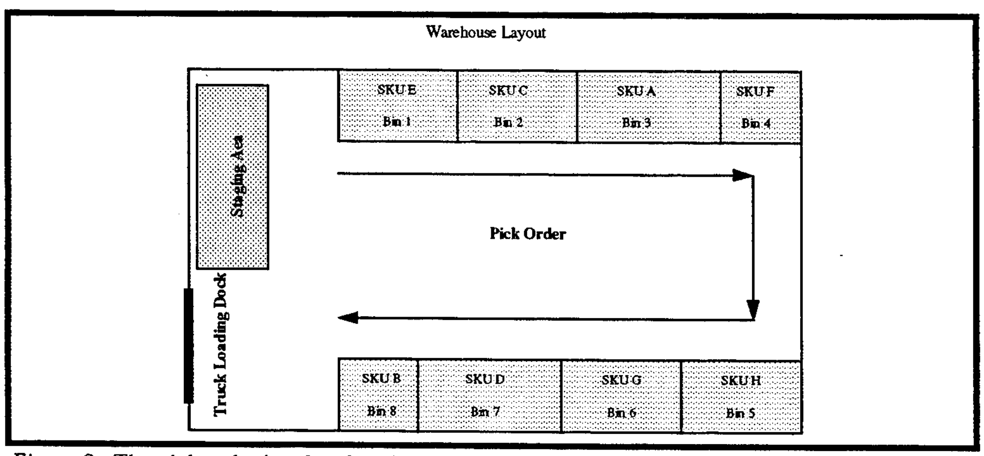


Figure 9. The pick order is related to the physical placement of SKUs in the warehouse. The pick order in the figure is: SKU E, SKU C, SKU A, SKU F, SKU H, SKU G, SKU D, SKU B. The staging area is a location where the palletized SKUs that comprise a truckload are stored prior to being placed in the truck. The truck loading dock is the point in the warehouse that pallets are placed into trucks.

8. SKU Database

An SKU database is critical for proper pallet and truck loading. A database maintains information concerning the physical characteristics of each SKU processed in the warehouse. Such a database specifies the dimensions and weight of each loaded container. Additionally, it contains information on full pallets: The number of containers per layer and the number of layers per full pallet. An SKU database also lists which SKUs are compatible. The SKU database normally includes a product description to provide additional documentation (Figure 10).

SKU	Description	Cont./ Layer	Layers/ Pallet	Pounds/ Cont.	Cont. Length	Cont. Width	Cont. Height	Compatable SKUs
1234	Product A	28	5	3.5	9.5	6.7	8.3	A,C,D,G
1235	Product B	6	6	11.0	29.3	9.3	3.6	A,D,E,F,G
2357	Product C	35	175	3.5	7.6	6.8	8.3	A,B,C,D,E,F
2578	Product D	4	4	27.0	20.8	16.8	10.9	B,D,F
3590	Product E	7	14	17.0	19.4	13.3	4.3	E,F,G
3998	Product F	9	7	29.8	17.1	11.5	9.0	A,B,C,D
4201	Product G	9	6	44.6	19.5	11.5	8.0	A,B,C,D,E,G

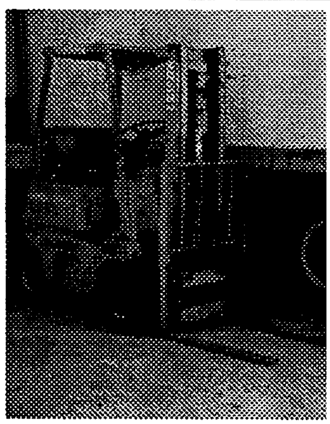
Figure 10. An SKU database provides information concerning the physical characteristics of each SKU processed in the warehouse. Dimensions and weight of loaded containers are specified. In addition information on full pallets, such as the containers per layer and layers per full pallet, is included. The SKU database normally includes a list of compatible SKUs.

9. Forklifts and Pallet Jacks

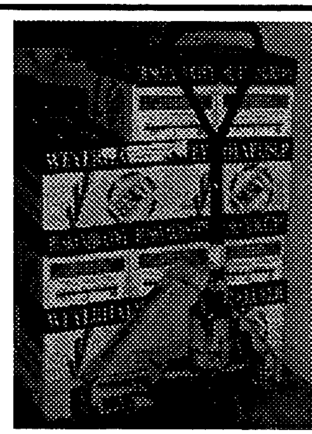
A forklift is a small vehicle with a power-operated, pronged platform at the front. This platform is placed under pallets and then lifted in order to move the pallets in the warehouse or into a truck (Figure 11). A typical forklift used in warehouse operations has a weight carrying capacity between 5,000 and 6,000 pounds (2,250-2,700 Kg).

A pallet jack is a hand operated conveyance designed to transport pallets short distances. Pallet jacks rely on hydraulics for lifting and human strength for movement. Their normal capacity ranges between 1,500 and 2,000 pounds (675-900 Kg).

Normally pallet heights and weights are limited by the capabilities of the forklifts and pallet jacks at the origin and destination. For example, if a customer order is being shipped to a destination that has only pallet jacks, pallet weight will be limited to 1,500-2,000 pounds.



Forklift



Pallet Jack

Figure 11. Pallets are transported by forklifts and pallet jacks. Forklift lifting capacity is normally between 5,000 and 6,000 pounds (2,250-2,700 Kg). Pallet jacks may be used to transport pallets short distances. The capacity of pallet jacks is normally between 1,500 and 2,000 pounds (675-900 Kg).

B. Truck Loading

1. Equipment

A truck consists of two components: a tractor and one or more trailers. Although trailers come in many different sizes, commonly ranging from 20 feet (6.1 m) to 53 feet (16.2 m), the industry standard is a single trailer with length 53 feet [Brown, 1995]. Truck internal widths range from 96 inches (244 cm) to 103 inches (262 cm). Truck internal heights normally range between 105 inches (263 cm) to 120 inches (300 cm).

Trucks each have a maximum net cargo weight that may legally be carried. This weight is determined by the length of the trailer and the number of axles.

A truck's axles support the load's weight. The amount of load weight supported by a given axle is dependent on the arrangement of the load within the truck. Additionally, the back axles on most trailers are movable within a range. Moving these axles shifts weight from back to front axle or vice versa (Figure 12). Knowledge of axle location is critical to proper load planning.

Every truck has an axle weight limit, defining the maximum amount of weight that may be supported by an axle. Axle weight limits vary from state to state.

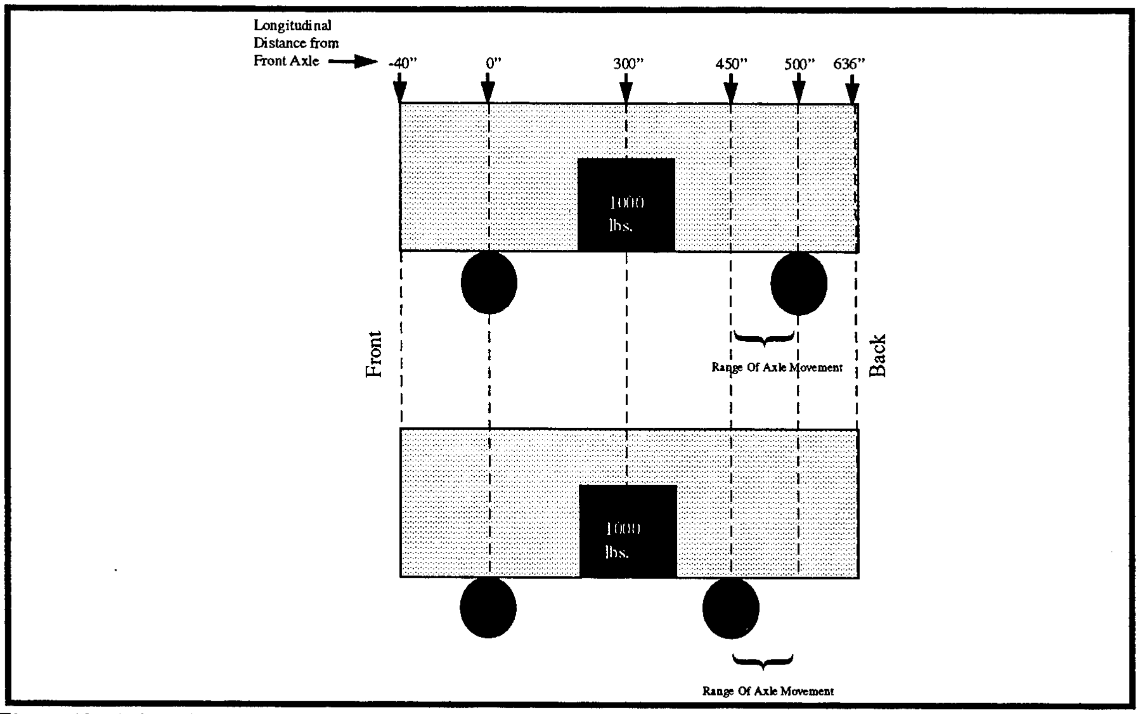


Figure 12. Axle weights are a function of load distribution and axle position. Pallet weight is distributed between the front and back axles and may be computed using the equality: (Distance from front axle) x (pallet weight) = (distance between axles) x (weight on back axle). The weight on front axle = (pallet weight) - (weight on back axle). Distances in front of the front axle are considered to be negative. For example, the back axle weight of the top figure = (300" x 1000 lbs.)/500" = 600 lbs.. The front axle weight = (1000 lbs. - 600 lbs.) = 400 lbs.. Movable axles allow load weight to be shifted from back to front axle or vice versa. In the lower figure the back axle has been moved 50 inches forward . The new back axle weight is 667 lbs and the new front axle weight is 333 lbs.. Weight has been shifted from front to back axle.

A trailer has three axes: Longitudinal, lateral and vertical. The longitudinal axis runs from the front wall to the back wall. A location on the longitudinal axis is measured as a distance from the front wall. The lateral axis runs from the left to right wall, looking forward. A location on the lateral axis is measured as a distance left or right of the longitudinal axis. The vertical axis is measured from the floor of the trailer to the ceiling (Figure 13). Locations in the trailer may be described with reference to the axes. For instance, the location of an axle may be given as a position on the longitudinal axis.

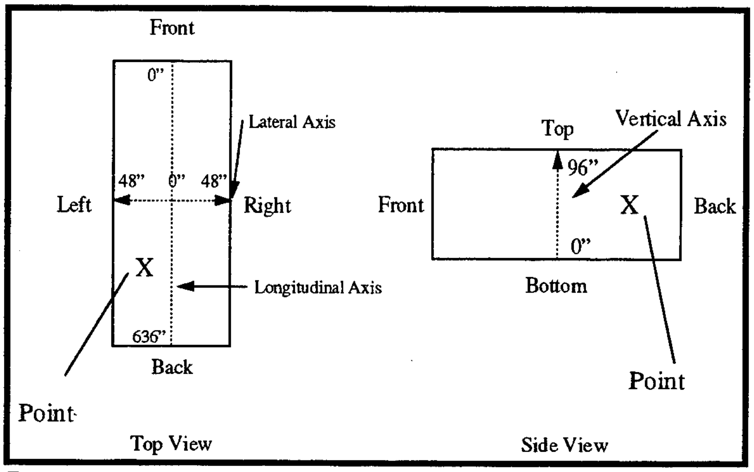


Figure 13 The axes of a trailer. The top view shows the longitudinal and lateral axes for a 53 foot truck with an interior width of 96 inches. The Side view shows the vertical axis for a trailer with a 96 inch height. A point in the trailer may be completely described with use of these referent axes. For instance the point labeled in the figure is 525 inches on the longitudinal axis, 20 inches left on the lateral axis and 50 inches on the vertical axis.

2. Loading Pallets Into Trucks

A load plan is a blueprint for placing full and mixed SKU pallets in a truck: It defines the position and orientation of every pallet in the load. Each load will have a number of possible load plans. For example, a load of 26 distinct pallets carried in a 53 foot truck would have more than $26! \approx 4.03 \times 10^{26}$ unique load plans.

The ease of loading and unloading pallets is one commonly used measure for selecting the "best" load plan. Pallet stacking requires additional time and increases the risk of damaging SKUs and thus, as a general rule, should be minimized. There are, however, several scenarios when pallet stacking becomes desirable. Obviously, stacking is required when there are more pallets than floor positions and weight limits permit full volume utilization. In addition, pallets will be stacked when driving conditions require shifting load weight to the forward axle to improve truck braking.

Similar SKUs should be placed in close proximity to each other in the truck. This facilitates the accounting of SKUs at the warehouse and destination and makes truck loading easier.

Individual pallets are formed into pallet pairs: An artifice used to explain truck loading methodology. A pallet pair is a set of one or two pallets that is loaded across the width of the truck (Figure 14). A pallet pair or two pallet pairs, one on top of the other, can form a pallet group. Pallet stacking is the combination of pallet pairs into pallet groups. The same issues that are important in pallet picking are important in pallet stacking. For instance, two pallets may be stacked if the SKUs on those pallets are compatible and the heavy pallet is not placed on top of the light pallet.

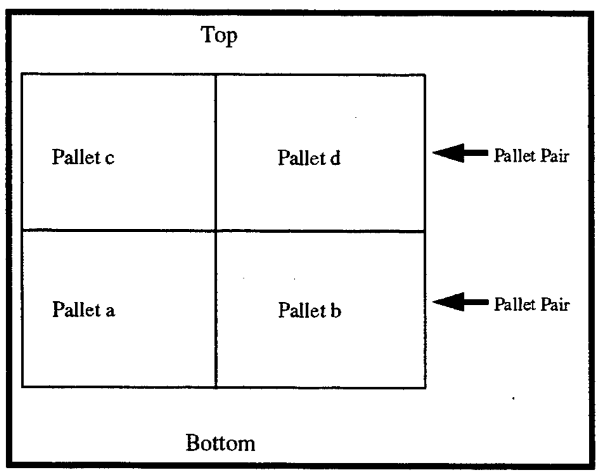


Figure 14. Pallet pairs and pallet groups. Pallets (a,b) and (c,d) form pallet pairs. The two pallet pairs combine to form a pallet group. Each group is unique. If the placement of any pallet is changed a new group is formed. Pallet groups may have 1-4 members (i.e. there may be as many as three empty locations in a group).

The crown of the road, the convex construction of most roads (Figure 15), may cause pallets to shift to the right side of the truck in the United States. If a pallet group consists of one pallet, that pallet should be placed on the right side to reduce shifting.

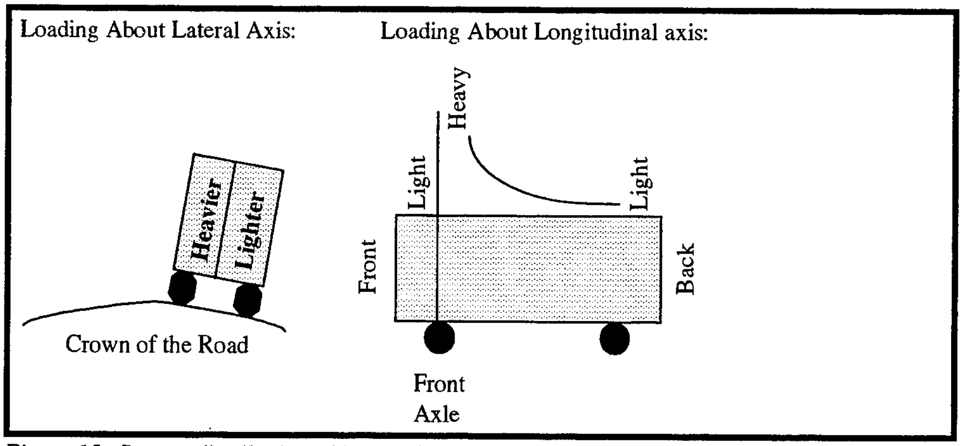


Figure 15. Proper distribution of load weight is critical in forming a stable load. If the load cannot be equally distributed about the lateral axis the left side should be heavier. This counteracts the effect of the crown of the road. The pallets forward of the front axle should be light. Behind the front axle the weight should be distributed from heavy to light.

A load must be stable. Each pallet should anchor every other pallet to reduce shifting during transport (Figure 16).

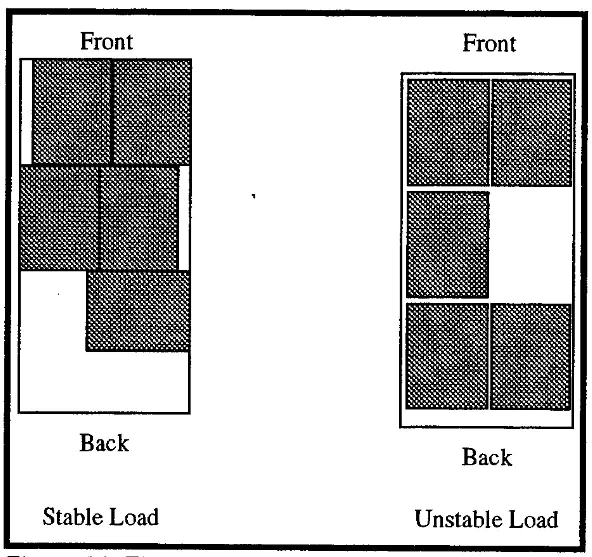


Figure 16. The load on the left is stable. Pallets could not easily shift during transport. The load on the right is unstable. The pallets on the right side of the truck are not anchored by other pallets and could shift forward and backward in the truck during transport. The single pallet on the left may slide due to the crown of the road.

A common "rule of thumb" used in the trucking industry is that each foot (0.31 m) along the longitudinal axis of the truck should be loaded with no more than 1000 pounds (450 Kg). For example, if a 53 foot truck has an axle weight limit of 40,000 pounds, then the thumb rule of 1000 pounds per foot along the longitudinal axis results in a front axle weight of approximately 20,000 pounds and a back axle weight of 33,000 pounds: Axle weights that are within legal ranges.

The weight of the load should be equally distributed about the lateral axis of the truck. If an equal distribution is not possible the left side of the truck should be heavier to counter the effect of the crown of the road. Pallets forward of the front axle should be light. Starting at the front axle the pallets should be loaded based on weight: from heavy to light (Figure 15).

3. Choosing the Right Truck

A number of different size trucks may be available to carry a given load. The cost of a truck is a function of many factors that may be unrelated to size. Given a list of trucks that have equal operating costs, the smallest truck capable of carrying the load is normally chosen.

4. Geometry of Loading Pallets into Trucks

Pallets are arranged in full trucks using one of two basic load patterns: The straight load pattern or the pinwheel load pattern. The straight load pattern has pallet pairs with both pallets having their 40-inch sides facing back. The location of the heaviest pallet alternates from right to left for successive pallet pairs. This maintains a rough balance of weight about the lateral axis of the truck. Loading two pallets with this pattern requires 48 inches along the longitudinal axis of the truck (Figure 17). The straight load pattern requires less time to load than any other pattern.

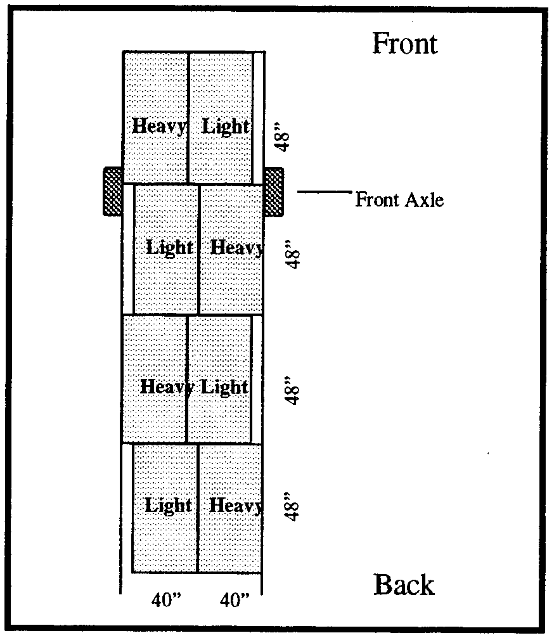


Figure 17. The straight load pattern. This pattern places two pallets, side-by-side, with their 40-inch sides facing back. This pattern requires the least time for loading.

The pinwheel load pattern has pallet pairs, with one pallet's 40-inch side facing back and the other pallet's 48-inch side facing back. A complete pinwheel consists of two contiguous pallet pairs, each with reverse rotational symmetry (Figure 18). The weight is distributed about the longitudinal and lateral axes of the trailer in the same manner as the straight load pattern. Loading four pallets using the pinwheel loading pattern requires 88 inches (224 cm) along the longitudinal axis and thus saves 8 inches (20 cm) compared to the straight loading pattern. This space savings allows an additional pair of pallets to be loaded for every six complete pinwheels. The last pallet pair loaded with the pinwheel pattern may be placed in the truck with both 40-inch sides facing back (Figure 19). The pinwheel pattern requires the forklift to load pallets by the 48-inch side where there may be no slots, increasing the loading difficulty and time required. Exclusive use of four-way pallets reduces this difficulty.

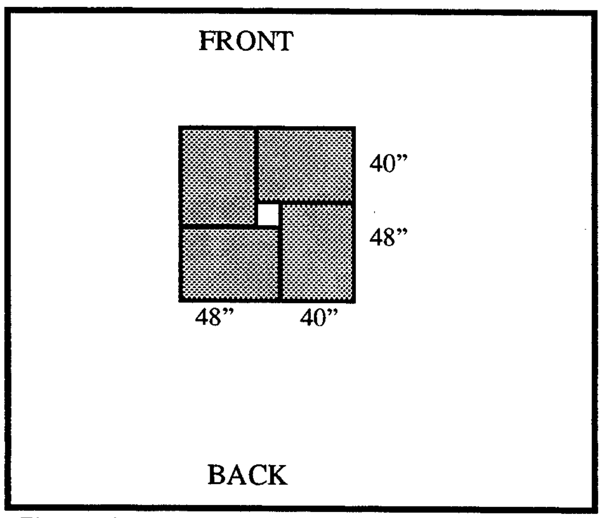


Figure 18. A complete pinwheel. The pinwheel pattern combines a pallet with its 40-inch side facing back and a pallet with its 48-inch side facing back. A complete pinwheel consists of two contiguous pallet pairs, each with reverse rotational symmetry.

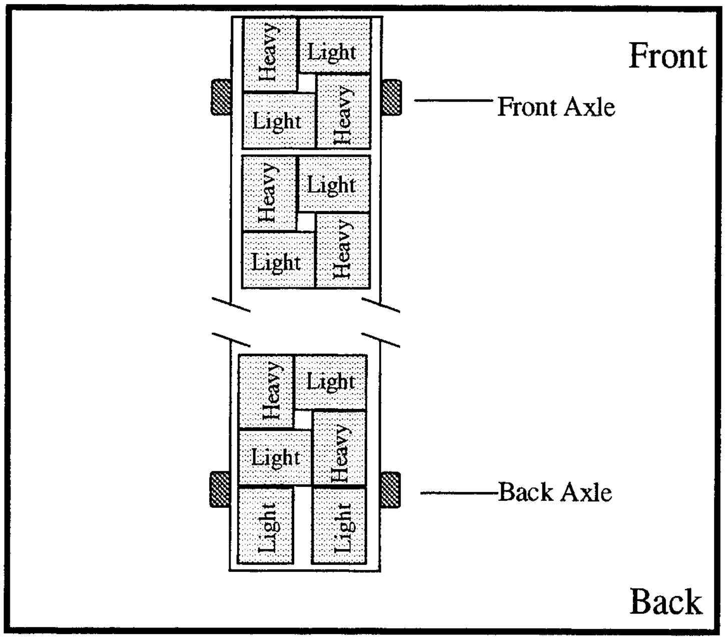


Figure 19. A truck loaded with the pinwheel pattern. The last pallet pair may be loaded with its 40-inch side facing back. Each pallet pair contains a heavy and light pallet. The placement of the heavy pallet alternates from left to right maintaining a rough balance about the lateral axis.

Loads that require pallet stacking normally utilize the straight load pattern. This is due to the increased difficulty associated with pinwheeling subsequent layers of pallets. The height of stacked pallets is generally limited to two pallets.

5. Loading Criteria

The method used to place pallets in a truck depends on many external factors. For instance, driving conditions, odd sized pallets or loose containers all affect pallet loading. It is impractical to allow for all of these factors when load planning. It is possible, however, to use multiple, perhaps conflicting, criteria that guide in choosing between load plans. A loading criterion is a stated objective that the loader has: It defines what characteristic a "good" load plan should have.

Two common criteria are minimum stacking and maximum cube utilization. Minimum stacking is appropriate when the time and effort required to load and unload the truck are of primary concern. This criterion results in minimum damage during transport.

The second criterion, maximum cube utilization, calls for stacking pallets to the maximum extent possible. This criterion is appropriate when driving conditions dictate that load weight be shifted to the front axle to aid in truck braking. This criterion is also appropriate when the user wishes the flexibility to handle oversized pallets. Pallet stacking places as many pallets as possible in the front of the truck.

6. Critical Load Factor

The critical load factor is the load characteristic (i.e., total weight or number of pallets) that is closer to the respective limitations of the truck. This influences arrangement of pallets in the truck. Consider, for example, a 53 foot truck with a net weight of 40,000 pounds. This truck is capable of carrying a maximum of 52 pallets (53 ft x 12 inches/ft x .021 straight load pallet positions/inch = 13.35 pallet positions. Disregarding fractional pallet positions and based on a pallet position holding a maximum of four pallets, this truck has a capacity of 13 x 4 = 52 pallets). The critical load factor for a load consisting of 40 pallets (77% pallet capacity) with a gross weight of 39,500 pounds (98.8% of weight capacity) would be weight.

III. CURRENT METHODOLOGY

In this section currently used methods for pallet picking and truck loading are discussed. The methods are divided into two types: Manual and automated methods.

A. Manual Methods

1. Pallet Picking

A customer order is normally assigned to a single forklift driver who prepares it for loading. A staging area in the warehouse is also assigned to each truck load.

The forklift driver prepares the customer order in three phases. In the first phase he compares each SKU's unloaded order quantity to its full pallet quantity. If a SKU's unloaded order quantity exceeds its full pallet quantity a full pallet is moved from the warehouse storage site to the staging area. The unloaded order quantity is then decreased by this full pallet quantity. This process is repeated until all SKUs on the customer order have unloaded order quantities less than full pallet quantities (Figure 20).

Customer Order			SKU Database	Full Pallets In Staging Area
SKU	Description	Quantity	Containers/Pallet	
1234	Product A	~~150~~ 10	140	A: 0, 1
1235	Product B	~~200, 164, 128, 92, 56~~ 20	36	B: 0 ,1 ,2 ,3, 4, 5
2357	Product C	15	6125	C: 0
2578	Product D	~~75, 59, 43, 27~~ 11	16	D: 0 ,1 ,2 ,3 ,4

Figure 20. Selecting full pallets. The first phase of pallet picking is to select full pallets. If a SKU's unloaded order quantity is greater than the full pallet quantity, a full pallet is moved from its storage location in the warehouse to the staging area and the unloaded order quantity is decreased by this full pallet quantity. The figure shows the customer order from figure 2 and part of the SKU data base from figure 10. Two hundred units of Product B have been ordered. There are 36 containers per pallet. Note that each time a full pallet is selected the unloaded quantity on the customer order decreases by the pallet quantity.

In the second phase the forklift driver picks mixed layer pallets. The driver places an empty pallet on the forklift. He then visits the storage site of each SKU on the customer order that has an unloaded order quantity greater than the layer quantity. The sequence that he stops at the storage sites is usually the pick order. The driver may add a layer of a SKU if it is compatible with all other SKUs previously placed on the pallet. Additionally, the new layer must not cause the pallet to exceed its desired height or weight. When no additional layers can be added the driver places the mixed layer pallet in the staging area. The driver repeats this process until no SKU on the customer order has an unloaded order quantity in excess of the layer quantity (Figure 21). This phase may be modified a bit if similar SKUs with the same dimension can be aggregated into full layers.

In the third phase the forklift driver combines the remaining "loose containers" of SKUs on the customer order into mixed SKU pallets. The forklift driver decides which SKUs to mix on a pallet and how to stack them. To achieve stability these pallets are usually shorter, approximately 30 inches. This phase is the most time consuming and presents the greatest risk of items being damaged in transit due to improper pallet picking.

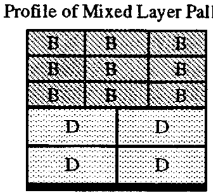
Customer Order

SKU	Description	Quantity
1234	Product A	10
1235	Product B	~~20~~, ~~14~~, ~~8~~, 2
2357	Product C	15
2578	Product D	~~11~~ ~~7~~, 3

SKU Database

Containers/Layer
28
6
35
4

Profile of Mixed Layer Pallet



Pick Order: C, A, D, B

Figure 21. Picking mixed layer pallets. The forklift driver will visit the storage site of each SKU on the customer order that has an unloaded order quantity greater than its layer quantity. The sequence in which sites are visited is based on the pick order shown in figure 9. If the SKU at the current site is compatible with the other SKUs on the pallet and does not exceed the desired height or weight for the pallet, a layer is added and the unloaded SKU quantity is decreased by the layer quantity. The figure shows the customer order from Figure 2 and part of the SKU data base from Figure 10. Two layers of D are placed on the pallet and then three layers of B.

2. Truck Loading Operations

Loading pallets onto trucks is time consuming and a difficult task. The forklift driver determines the configuration of the pallets based on his experience. This involves fitting pallets inside the truck in a three dimensional pattern. The cost of an improperly loaded vehicle is high: SKUs may be damaged in transit, time may be lost unloading and reloading the truck and heavy fines may be levied on trucks that are loaded outside net weight or axle weight limitations.

B. Automated Methods

Computer programs are commercially available that purport to solve portions of the pallet and truck loading problem. Advanced Pack and Stack™ (APS) and Advanced Order Picking™ (AOP) [Advanced Logistics Systems, 1995c, 1995b] and Mixpal™ [TOPs Engineering Corporation, 1991b] are examples of commercial products that are used in pallet picking. Common capabilities include choosing the correct container for a SKU and picking full and mixed SKU pallets. Advanced Loading System™ [Advanced Logistics Systems, 1995a] and Maxload™ [TOPs Engineering Corporation, 1991a] are examples of commercial products that are used in truck loading. Common capabilities include selecting a load plan and nominating the best truck size. None of these packages claim to honor product compatibility in pallet picking or truck loading, nor do any offer axle weight balancing. These programs are proprietary and no open literature articles document or justify the methodology they use. Haessler et. al [1990] present a heuristic for loading low density containers of varying SKUs and dimensions into trucks and railcars. This heuristic is reviewed in detail in Chapter V.

This thesis is motivated by the apparent economic importance of pallet picking and truck loading and the lack of supporting open literature on how best to do it.

IV. PATL: A PALLET AND TRUCK LOADING HEURISTIC PROCEDURE

In this section a heuristic procedure that prepares a customer order for transport is introduced. A heuristic procedure is an intuitively designed procedure that does not guarantee an optimal solution but will provide a feasible solution in real time [e.g., Hillier and Lieberman, 1990]. The basic concept is very simple: Decision rules currently used are automated to provide a feasible loading solution in "real time". The methods are divided into two sections: Pallet picking and truck loading operations.

A. Pallet Picking

1. Required Input

The customer order is the primary input. It must contain the items ordered, identified by SKU, and quantities required. The SKU database is another required input and must include container dimensions, weight and the number of containers per full pallet and full layer. Accuracy of the SKU database is paramount. Lastly, the pick order is required.

2. Assumptions

It is assumed that all SKUs are packaged in rectangular containers. Further, lateral dimensions of a container may be exchanged, but height is fixed.

We assume a preference between pallet types: Full pallets are preferred to mixed layer pallets and mixed layer pallets to mixed SKU pallets.

We assume that the load-bearing strength of each container is sufficient to support any item, or combination of items, placed on top of it. This last assumption implies that the number of layers on a mixed layer pallet is determined solely by the capability of the handling equipment and the interior dimensions of the truck. This is a restricting simplifying assumption.

3. Solution Procedure

The PATL heuristic generates pallets in four phases. In the first phase the customer order is sorted based on the pick order.

In the second stage full pallets are selected. The unloaded order quantity is decreased by this full pallet quantity. This process is repeated until all SKUs on the customer order have unloaded order quantities less than their full pallet quantities. The pseudocode for this procedure is contained in Figure 22.

```
For every SKU on the customer order do
    While unloaded order quantity is greater than pallet quantity do
                    Select full pallet
                    Decrease order quantity by pallet quantity
    end
end
```

Figure 22. Full pallets are selected from those SKUs that have unloaded order quantities greater than the full pallet quantity. This procedure is repeated until every SKU's unloaded order quantity is less than its full pallet quantity.

The third stage picks mixed layer pallets. In pick order a full layer of a SKU is added to the pallet if the unloaded order quantity is greater than the layer quantity and adding the layer will not exceed the desired height or weight for the pallet. Additionally, for the layer to be added it must be compatible with all other SKUs already on the pallet. If a layer is added, the unloaded order quantity is decreased by the full layer quantity. When no more SKUs can be added to the current pallet, a new pallet is started. Mixed SKUs are built in this manner until no SKU has an unloaded order quantity in excess of the layer quantity. The pseudocode for this procedure is in Figure 23.

```
While the order quantity of any SKU is greater than layer quantity do
Start new Pallet
        for each SKU on the sorted customer order do
                while (current SKU order quantity is greater than layer quantity)
                and (a layer of the current SKU can be added without exceeding height
                or weight limits)
                and (current SKU is compatible with other SKUs on pallet) do
                        add layer of current SKU to pallet
                        decrease order quantity by layer quantity
                end
        end
end
```

Figure 23. A mixed layer pallet contains several layers, each having only one SKU. The height and weight of a mixed layer pallet is limited by the dimensions of the truck and capabilities of the handling equipment. In addition, all SKUs on the pallet must be compatible.

The fourth stage is to print a list of SKUs not loaded on the full or mixed layer pallets. These SKUs will be manually formed into mixed SKU pallets or carried as unpalletized loose cargo at the back of the truck.

The structure for the pallet picking portion of this heuristic is contained in figure 24.

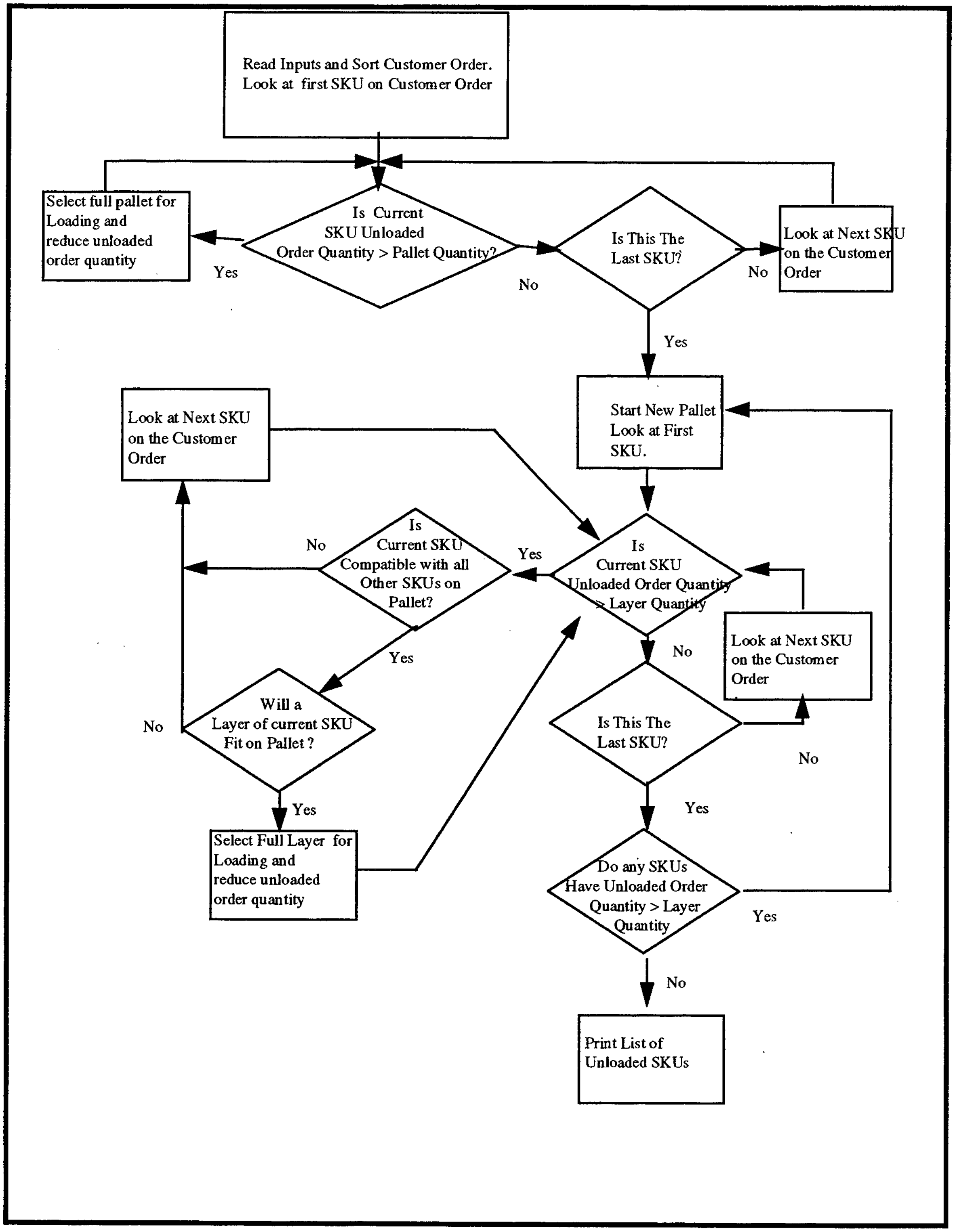


Figure 24. Rough description of pallet building portion of PATL.

4. Output

The output from the pallet picking procedure lists the full and mixed SKU pallets selected for loading (Figure 25). Each pallet is assigned an alpha-numeric identifier and has its height, weight, and contents identified. Unloaded SKUs are listed separately.

Loaded SKUs

Pallet ID	Height	Weight	Contents
AA	60.0	1200	5 Layers product A
AB	55.3	900	6 Layers product B
AC	61.5	1800	6 Layers product B
AD	48	2100	2 Layers product B 4 Layers produst C
AE	65	1200	3 Layers product C 3 Layers product E

Unloaded SKUs

SKU	Quantity
A	10
B	20

Figure 25. Output from the pallet building procedure identifies full and mixed Layer pallets. In addition unloaded SKUs, SKUs that were not placed on a full or mixed layer pallet, are listed.

B. Truck Loading Operations

1. Assumptions

We assume that full and mixed layer pallets may be topped with a compatible pallet. Additionally, we assume that the preferred order when stacking pallets is light on top of heavy and that pallets are stacked no more than two deep.

We assume the distribution of weight on a pallet to be uniform, thus the center of gravity and the geometric center of the pallet are collocated. This assumption simplifies the computations required to determine axle weights.

We assume that SKUs not loaded during pallet picking procedure are left unpalletized: They are separately placed into the truck after all pallets have been loaded. This assumption may be relaxed to allow for the use of mixed SKU pallets but the user must add the height, weight and contents of each mixed SKU pallet to the output created by the pallet picking procedure.

Normally the user will define the desired truck size for each load. If the user has no preference for truck size we assume trucks should be selected based on length: Shorter is better. Ties are broken by minimum height and then minimum width.

2. Required Input

The output from the pallet picking procedure is the primary input of the truck loading procedure. A SKU database is required. The length, width, height, axle location, net load weight, and axle weight are required for each truck on the list of available trucks. Lastly, the user will be prompted for any special load considerations such as the necessity to leave space at the rear of the trailer, truck handling considerations, or other stacking related issues.

3. Pallet Positions

It is necessary to define the location of each pallet in the truck. To do this *PATL* separates the interior of the truck into rectangular solids of space called *pallet positions* where a pallet group may be placed. A pallet position is characterized by its length, width, height and position in the truck. The width and height of a pallet position are the same as the internal dimensions of the truck. The length of the pallet position is dependent on the type of loading procedure used. Pallet positions are oriented continuously along the longitudinal axis of the truck and numbered sequentially from front to back of truck (Figure 26).

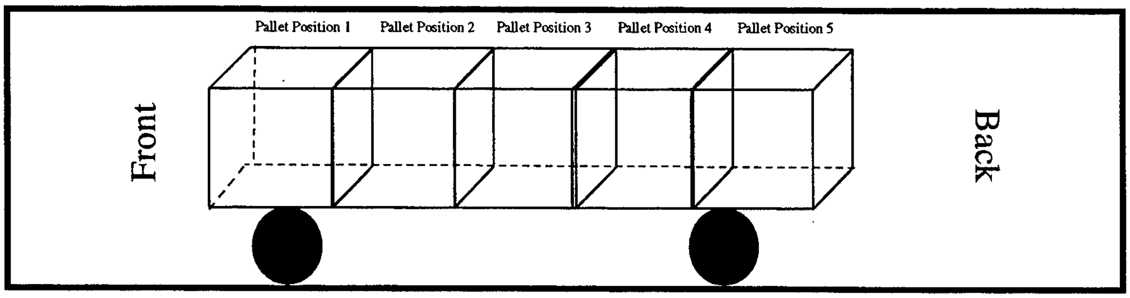


Figure 26. Pallet positions define a rectangular solid of space within the truck. A pallet position is characterized by its length, width, height and position in the truck. The width and height of a pallet position are the same as the interior dimensions of the truck. The length is determined by the loading procedure used. One pallet group may be placed in each pallet position.

4. Loading Procedures

Procedures used by *PATL* to determine load plans are discussed in this section. The procedures can be separated into two groups: Procedures for single-layer loads and procedures for two-layer loads.

a. Procedures for Single-Layer Loads

The Straight-Load-Single-Layer (SLSL) procedure loads a single layer of pallets using the straight load pattern. Each pallet position will have zero, one, or two pallets. Pallet positions that contain two pallets have the 40" sides of both pallets facing back. Pallet positions that contain one pallet are loaded with that pallet's 48" side facing back.

Pallet positions are ordered based on the number of pallets they have. Pallet positions with two pallets will be in front of those with one pallet, which are in front of pallet positions with zero pallets (Figure 27).

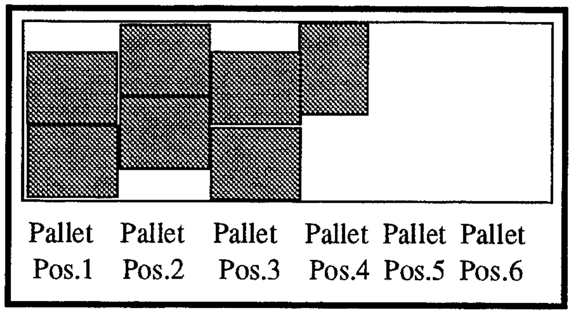


Figure 27. The Straight-Load-Single-Layer Procedure loads a single layer of pallets in the straight load pattern. Pallet positions are ordered based on the number of pallets they have: Positions with two pallets will be in front of positions with one, etc.

The pseudocode for this procedure is contained in Figure 28.

```
Do (For each pallet position)
        If (you are loading a pallet position in front of the forward axle)
        and (the combined weight of the lightest two unloaded pallets is less than 4000 pounds)
        then
                Load the lightest two unloaded pallets in this position with their 40" side
                facing aft.
                Place the heavier pallet on the side of the truck opposite the heaviest pallet
                in the previous pallet position. If this is the first pallet position then place
                the heavier pallet on the left.

        If (you are loading a pallet position in front of the forward axle)
        and (the combined weight of the lightest two unloaded pallets is more than 4000 pounds)
        then
                load the lightest unloaded pallet in this position with its 48" side facing aft

        If (you are loading a pallet position behind the forward axle) then
                If (the combined weight of the heaviest and lightest unloaded pallets is less than
                4000 pounds) then
                    load the lightest and heaviest unloaded pallets with their 40" side facing aft
                    Place the heavier pallet on the side of the truck opposite the heaviest
                    pallet in the previous pallet position.

                If (the combined weight of the heaviest and lightest unloaded pallets is more
                than 4000 pounds) then
                    load the heaviest unloaded pallet with its 48" side facing aft.
```

Figure 28. The straight load pattern places zero, one or two pallets in each position. Pallet positions with two pallets have both pallets loaded with their 40-inch (102 cm) sides facing back. Pallet positions with one pallet have the 48 inch side facing aft.

The Pinwheel-Load-Single-Layer (PLSL) procedure loads a single layer of pallets in the pinwheel load pattern. Pallet positions will contain zero, one or two pallets. Pallet positions that contain two pallets have one pallet with its 40 inch side facing back and one with its 48 inch side facing back. The last pallet position may be loaded using the straight load pattern. The pseudocode for this procedure is contained in Figure 29.

```
If (You have enough space behind rear axles to load 2 pallets) and
        (after you have loaded all pinwheels you still have two pallets to load) then
                Reserve the 2 lightest unloaded pallets for the end of the truck

        If (You have enough space behind rear axle to load 2 pallets) and
        (after you have loaded all pinwheels you still have one pallet to load) then
                Reserve the lightest pallet for the end of the truck

        If (You have enough space behind rear axle to load 1 pallet {40"-48"}) and
        (after you have loaded all pinwheels you still have one pallet to load) then
                Reserve lightest pallet for the end of the truck

        For each pallet position in the truck do
                If (you are loading a pallet position forward of the front axle) and
                (lightest 2 pallets weight less than 4000 pounds) then
                        Load the lightest two unloaded pallets in the pinwheel pattern

                If (you are loading a pallet position behind the forward axle) and
                (the lightest unloaded pallet and the heaviest unloaded pallet weigh less than 4000
                pounds) then
                        Load the lightest and heaviest unloaded pallet

        If (You have reserved 1 pallet to load at the end of the truck)
                Load this pallet with its 48" side facing aft
        If (You have reserved 2 pallets to load at the end of the truck)
                Load these pallets with their 40" sides facing aft
```

Figure 29. The pinwheel pattern loads zero, one or two pallets in each pallet position. Pallet positions with two pallets will have one pallet with its 40" (102 cm) side facing back and one pallet with its 48" (122 cm) side facing back. The last pallet position may be filled using the straight load pattern.

b. Procedures for Two-Layer Loads

The Straight-Load-Stack-Heavy (SLSH) procedure is used when maximum cube utilization is the loading criterion and weight is the critical load factor. This procedure seeks to load the maximum allowable weight in each pallet position. SLSH has two stages. In the first stage pallet groups are formed. Every subset permutation of four or fewer pallets is examined. The heaviest subset permutation that meets pallet stacking and truck loading requirements is selected. In the case of a tie, the subset permutation with the greatest number of pallets is chosen. When two subset permutations have a common weight and the same number of pallets, the first permutation considered is chosen. This procedure is repeated until all pallets have been placed in a pallet group.

The second stage of the SLSH procedure arranges the pallet groups within the truck. The pallet positions in front of the front axle are filled with the lightest unloaded pallet group that has three or more pallets. Behind the front axle pallet positions are filled with the unloaded pallet group that has the most pallets. In the case of a tie, the heaviest unloaded pallet group is selected. A pallet group with more than one member will have a right side and a left side. The pallets are arranged so that the heavier side alternates from right to left along the longitudinal axis of the truck. The pseudocode for this procedure is contained in Figure 30.

The Straight-Load-Stack-Volume (SLSV) procedure is used when maximum cube utilization is the loading criterion and the number of pallets is the critical load factor. This procedure seeks to load the maximum number of pallets in each pallet position. SLSV has two stages. In the first stage pallet groups are formed. Every subset permutation of four or fewer unloaded pallets is examined. The subset permutation that has the greatest number of pallets and meets pallet stacking and truck loading requirements is selected. In the case of a tie, the heaviest subset permutation is chosen. This procedure is repeated until all pallets have been placed in a pallet group. Figure 31 contains the pseudocode for the first stage of this procedure. The second stage is identical to the second stage of the SLSH procedure.

```
Repeat
        Do (Look at every subset permutation of four or fewer unloaded pallets)
                Group the heaviest permutation whose members are compatible
                Record action
        Until all pallets are placed into a group


For (every pallet position in the truck) do
        If (The pallet position is forward of the forward axles) do begin
                Load the lightest unloaded group from those groups that have
                3 or 4 pallets
        If ( The pallet position is aft of the forward axle) do begin
                Load the group that has the most pallets. Break ties with the
                heaviest pallet.
```

Figure 30 The Straight-Load-Stack-Heavy (SLSH) procedure is used when weight is the critical load factor: It loads the maximum amount of weight in each pallet position.

```
Repeat
  Do (Look at every subset permutation of four or fewer unloaded pallets)
          Group the permutation with the most compatible members Break ties
          with weight
          Record action
Until all pallets are placed into a group
```

Figure 31. The first stage of the Straight-Load-Stack-Volume (SLSV) procedure. SLSV is used when maximum cube utilization is the loading criterion and the number of pallets is the critical load factor. This procedure loads the maximum number of pallets in each pallet position.

The Straight-Load-Minimum-Stacking (SLMS) procedure is used when minimum stacking is the loading criterion and the single layer loading procedures fail to fit the load into a truck. This procedure plans the load using the maximum amount of single-layered, straight-loaded pallet positions and is completed in two stages. The first stage determines how many pallet positions must have four pallets assigned to them so that a maximum number of pallet positions will have two pallets assigned to them.

The second stage of the SLMS procedure selects the pallet groups required by step one. Every subset permutation of four unloaded pallets is examined. The first subset permutation that satisfies the pallet stacking and truck loading requirements is selected. The pseudocode for the first and second stages of this procedure is contained in Figure 32.

```
Do (Determine the number of pallet groups that require four pallets)

Repeat
        Do (Look at every subset permutation of four unloaded pallets)
           Group the first subset permutation whose members meet pallet stacking and truck loading
                    requirements
           Record action
Until  (The number of required pallet groups with four pallets have been formed)

For (Each pallet position that is to receive a pallet group with four pallets)
        load the lightest unloaded pallet group

For (The remaining pallet positions)
        Load the remaining pallets using the SLSL procedure
```

Figure 32. The Straight-Load-Minimum-Stacking (SLMS) procedure. This procedure is used when minimum stacking is the loading criterion and the single layer procedures failed to produce an acceptable loadplan. It plans the load using the maximum amount of single-layered, straight-loaded pallet positions. The shaded portion of the code determines the loading of the pallet positions that require four pallets. The unshaded portion of the code is used to load the remainder of the pallets, two to a pallet position, with the SLSL procedure.

5. Load Testing

Once a load plan has been produced it is checked to ensure suitability. Load testing is conducted in two steps. The first step ensures that the load plan fits the desired truck. If the pallet groups do not fit inside this truck, then the smallest truck that they do fit is selected and an error message is generated.

Axle weights are determined in the second step. If a load plan exceeds truck axle weights limits, the pallets in the load plan are shuffled, one at a time, to shift weight from the heavy axle to the light axle. If this shuffling process does not result in a load plan with legal axle weights, an error message is generated.

A rough description of the truck loading procedure is contained in Figure 33.

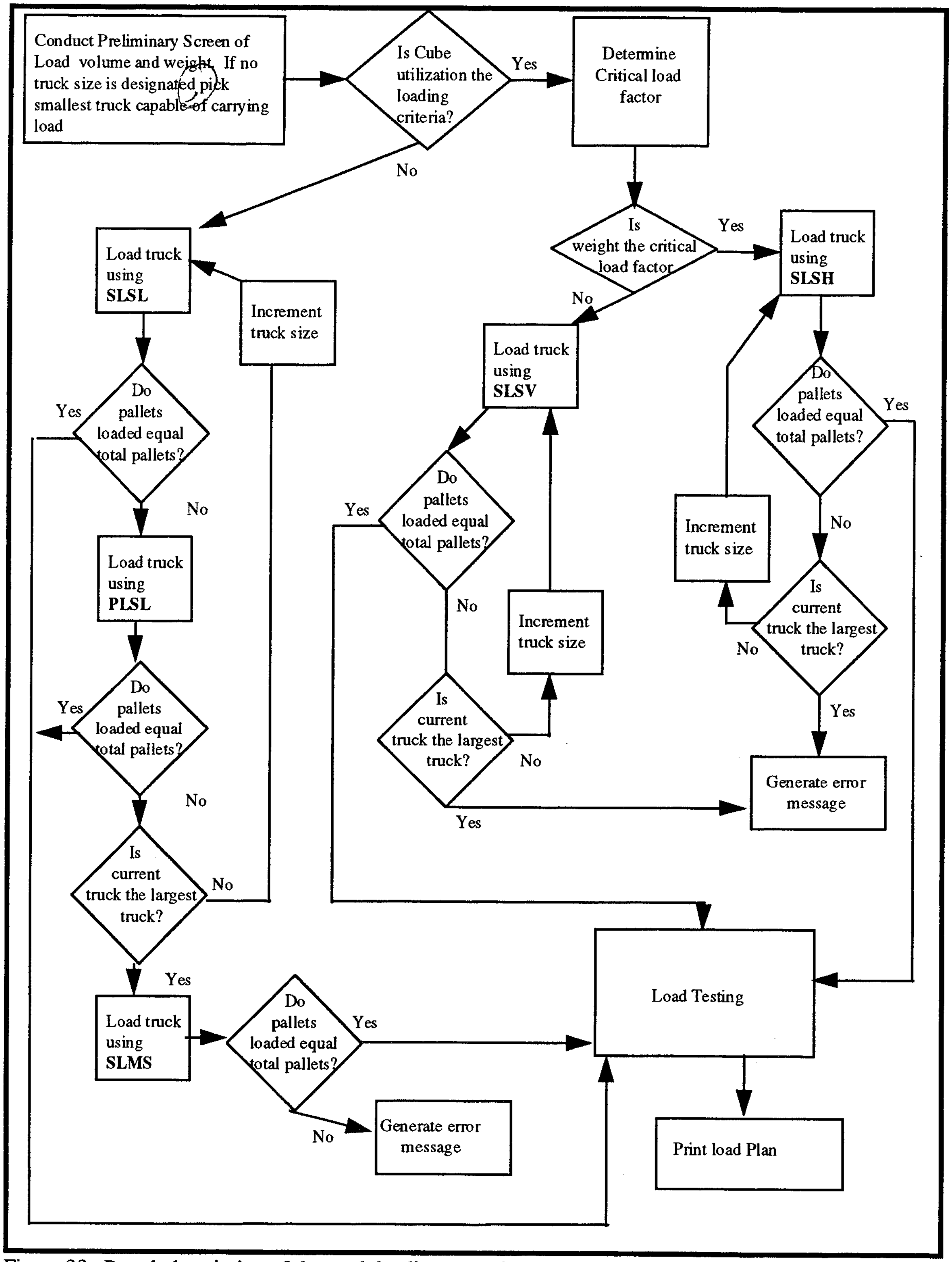


Figure 33. Rough description of the truck loading procedure.

V. REAL-WORLD EXAMPLES

Two commercial customer orders are introduced and the output from *PATL* is examined. We then introduce a customer order for products shipped by the Defense Logistics Agency (DLA) and examine the output from the truck loading portion of *PATL*.

A. High Volume Customer Order

A customer order is created using the SKU database from a major distributor of household products. The customer order is designed so that volume is the critical load factor (Figure 34). SKU compatibility is based on product class and may be determined with the matrix in Figure 35. From this customer order the pallet picking portion of *PATL* picks 44 full pallets and 4 mixed layer pallets. Several SKUs have loose containers remaining after the pallet picking process (Figure 36). The pallet picking required for this customer order required less than 2 seconds of computing time on a desktop computer with a 30486/33 processor.

SKU	!Name	cse/lay	lay/pal	len	wid	ht	wt	class	Quant
100012	Hvy Duty clnr 8/32	12	4	13.4	11	11.9	20	liq	50
100026	Abrasive clnr 9/26	23	4	10.3	8.3	8.6	11.8	liq	724
100921	Dry bleach 6/14	14	8	12.8	10	6.5	17.7	dry	120
200707	Orig. flvr drs 16z	26	4	8.6	6.8	9.1	11.8	fod	175
635034	Dryer towels	3	6	29	15	9.3	20.0	nfp	100
635888	Dryer towels 6/1	6	8	21.5	11	5.0	5.8	nfp	450
745902	Ant trap 98/6	3	4	34.6	16	9.9	23.2	pos	200
745905	Ant trap 12/8	50	6	7.8	4.9	6.9	1.2	pos	1250

Figure 34. A customer order that has volume as its critical load factor and the associated SKU database. Commodity classes include liquid (LIQ), dry goods (DRY), food (FOD) and poison (POS). Quantities shown are in cases.

SKU Compatibility Matrix

TOP LAYER

BOTTOM LAYER	LIQ	DRY	FOD	NFP	POS
LIQ	X	X	X	X	X
DRY	X	X	X	X	X
FOD			X	X	
NFP			X	X	
POS				X	X

Figure 35. SKU compatibility is determined by product class. The product classes in this matrix are liquid (LIQ), dry goods (DRY), food (FOD), non-food products (NFP) and poisons (POS). This matrix illustrates which product classes may be stacked on top of other product classes. For example, liquids may be placed on top of other liquids or dry goods.

Pallets generated by PATL for a high volume customer order

ID	HT	WT	SKUS/LYRS
M4	25.8	814	100026 3
M3	27.9	180	635034 3
M2	33.2	718	635888 3 200707 2
M1	26.7	638	745905 1 745902 2
F44	47.6	960	100012 4
F43	34.4	1085	100026 4
F42	34.4	1085	100026 4
F41	34.4	1085	100026 4
F40	34.4	1085	100026 4
F39	34.4	1085	100026 4
F38	34.4	1085	100026 4
F37	34.4	1085	100026 4
F36	52.0	1982	100921 8
F35	36.4	1227	200707 4
F34	55.8	360	635034 6
F33	55.8	360	635034 6
F32	55.8	360	635034 6
F31	55.8	360	635034 6
F30	55.8	360	635034 6
F29	40.0	278	635888 8
F28	40.0	278	635888 8
F27	40.0	278	635888 8
F26	40.0	278	635888 8
F25	40.0	278	635888 8
F24	40.0	278	635888 8
F23	40.0	278	635888 8
F22	40.0	278	635888 8
F21	40.0	278	635888 8
F20	39.6	278	745902 4
F19	39.6	278	745902 4
F18	39.6	278	745902 4
F17	39.6	278	745902 4
F16	39.6	278	745902 4
F15	39.6	278	745902 4
F14	39.6	278	745902 4
F13	39.6	278	745902 4
F12	39.6	278	745902 4
F11	39.6	278	745902 4
F10	39.6	278	745902 4
F9	39.6	278	745902 4
F8	39.6	278	745902 4
F7	39.6	278	745902 4
F6	39.6	278	745902 4
F5	39.6	278	745902 4
F4	41.4	360	745905 6
F3	41.4	360	745905 6
F2	41.4	360	745905 6
F1	41.4	360	745905 6

Total Palletized Weight = 23880

Total Pallets = 48

LOOSE SKUS

SKU#	NAME	QUANTITY
745905	Ant trap	0
745902	Ant trap	2
635888	Dryer Towels	0
635034	Dryer Towels	1
200707	Orig. flv	19
100921	Dry Bleach	8
100026	Abrasive	11
100012	heavy dut	2

Figure 36. List of full and mixed SKU pallets picked by PATL from a high volume customer order. A pallet is identified by an alpha-numeric code (the first column in the table). The first letter of this code indicates if the pallet is full or mixed: Full pallets begin with an 'F', mixed pallets begin with an 'M'. Additionally, the SKUs on each pallet and the layers of each SKU are listed. For example, the first pallet listed is mixed and carries 3 layers of SKU 100026. If a pallet carries more than one SKU, SKUs are listed from the bottom of the pallet up.

This load is to be carried in a trailer 53 feet long, 103 inches wide with a height of 120 inches. The maximum net cargo weight for this truck is 60,000 pounds (27,000 Kg). The front and back axle locations are 60 inches (153 cm) and 575 inches (1466 cm), respectively, measured from the front of the trailer along the longitudinal axis. The axle weight limit in California for this truck is 40,000 pounds (18,000 Kg).

The critical load factor for the pallets contained in Figure 35 is volume and thus *PATL* uses the SLSV procedure. The resultant load plan is contained in Figure 37. The axle weights are 16,907 pounds (7,608 Kg) and 5,956 pounds (2,680 Kg) for the front and back axles respectively.

Load Plan for High Volume Customer Order

	ID	WT	POS	SKUs
Pallet Position 1	F44	960	24.0	100012
	F43	1085	24.0	100026
	M4	814	24.0	100026
	M3	180	24.0	635034
Pallet Position 2	F42	1085	72.0	100026
	F41	1085	72.0	100026
	M2	718	72.0	200707 635888
	M1	638	72.0	745902 745905
Pallet Position 3	F40	1085	120.0	100026
	F39	1085	120.0	100026
	F38	1085	120.0	100026
	F34	360	120.0	635034
Pallet Position 4	F37	1085	168.0	100026
	F36	1982	168.0	100921
	F33	360	168.0	635034
	F32	360	168.0	635034
Pallet Position 5	F35	1227	216.0	200707
	F31	360	216.0	635034
	F30	360	216.0	635034
	F29	278	216.0	635888
Pallet Position 6	F28	278	264.0	635888
	F27	278	264.0	635888
	F26	278	264.0	635888
	F25	278	264.0	635888
Pallet Position 7	F24	278	312.0	635888
	F23	278	312.0	635888
	F22	278	312.0	635888
	F21	278	312.0	635888
Pallet Position 8	F20	278	360.0	745902
	F19	278	360.0	745902
	F18	278	360.0	745902
	F17	278	360.0	745902
Pallet Position 9	F16	278	408.0	745902
	F15	278	408.0	745902
	F14	2 78	408.0	745902
	F13	278	408.0	745902
Pallet Position 10	F12	278	456.0	745902
	F11	278	456.0	745902
	F10	278	456.0	745902
	F9	278	456.0	745902
Pallet Position 11	F8	278	504.0	745902
	F7	278	504.0	745902
	F6	278	504.0	745902
	F5	278	504.0	745902

Figure 37. The load plan generated by SLSV for customer order shown in Figure 34. The first pallet listed in each pallet position is placed on the bottom left-hand side, looking forward, of that pallet position. The second pallet is on the bottom, right-hand side. The third pallet is on the top, left-hand side and the fourth pallet is on the top right-hand side. Pallet weight and the distance from the front of the trailer to the geometric center of the pallet are also shown. This distance is used to compute axle weights.

B. High Weight Customer Order

Using the same SKU database a second customer order is created so that weight is the critical load factor (Figure 38). The SKU compatibility matrix in Figure 35 applies. From this customer order the pallet picking portion of *PATL* picks 37 full pallets, 2 mixed layer pallets and leaves 33 loose containers (Figure 39). The pallet picking for this customer order required under 2 seconds computing time on a desktop personal computer.

SKU	!Name	! cse/lay	lay/pal	len	wid	ht	wt	class	quant
100012	Hvy Duty clnr 8/32	12	4	13	11	11.9	20	liq	110
100013	Hvy Duty clnr 4/1ga	9	3	13	13.3	12.6	36.6	liq	250
100014	Hvy duty clnr 4/128	9	3	13	13.5	12.8	36.5	liq	200
100026	Abrasive clnr 9/26	23	4	10	8.3	8.6	11.8	liq	724
100104	Bleach 6/gal	7	5	20	13	12.6	58.1	liq	150
100295	Dry Cleaner	10	5	16	11	10.4	42.6	dry	100
100921	Dry bleach 6/14	14	8	12	10	6.5	17.7	dry	120
537001	Scrub pads	4	3	23	20	20	28.0	nfp	60

Figure 38. A customer order that has weight as its critical load factor and the associated SKU database.

Pallets generated by PATL for a high weight customer order

ID	HT	WT	SKUs/LAYERS
M1	25.8	814.2	100026 3
M2	37.3	975.2	100104 1 100014 1 100012 1
F37	47.6	960.0	100012 4
F36	47.6	960.0	100012 4
F35	37.8	988.2	100013 3
F34	37.8	988.2	100013 3
F33	37.8	988.2	100013 3
F32	37.8	988.2	100013 3
F31	37.8	988.2	100013 3
F30	37.8	988.2	100013 3
F29	37.8	988.2	100013 3
F28	37.8	988.2	100013 3
F27	37.8	988.2	100013 3
F26	38.4	985.5	100014 3
F25	38.4	985.5	100014 3
F24	38.4	985.5	100014 3
F23	38.4	985.5	100014 3
F22	38.4	985.5	100014 3
F21	38.4	985.5	100014 3
F20	38.4	985.5	100014 3

ID	HT	WT	SKUs/LAYERS
F19	34.4	1085.6	100026 4
F18	34.4	1085.6	100026 4
F17	34.4	1085.6	100026 4
F16	34.4	1085.6	100026 4
F15	34.4	1085.6	100026 4
F14	34.4	1085.6	100026 4
F13	34.4	1085.6	100026 4
F12	63.0	2033.5	100104 5
F11	63.0	2033.5	100104 5
F10	63.0	2033.5	100104 5
F9	63.0	2033.5	100104 5
F8	52.0	2130.0	100295 5
F7	52.0	2130.0	100295 5
F6	52.0	1982.4	100921 8
F5	60.0	336.0	537001 3
F4	60.0	336.0	537001 3
F3	60.0	336.0	537001 3
F2	60.0	336.0	537001 3
F1	60.0	336.0	537001 3

Total Palletized Weight = 43157.3
Total Pallets = 38

LOOSE SKUS

SKU#	NAME	QUANTITY
537001	Scrub pads	0
100921	Dry Bleach 6/14	8
100295	Dry clnr	0
100104	Bleach 6/gal	3
100026	Abrasive cnlr 9/26	11
100014	HVY Dutyclnr4/128	2
100013	Hvy Dutyclnr4/1 gal	7
100012	heavy duty cleaner	2

Figure 39. List of full and mixed pallets picked by PATL for the customer order shown in Figure 38.

This load is to be carried in the same 53-foot truck described in the previous section. The SLSH procedure is used to plan the load. The resultant load plan is contained in Figure 40. The axle weights are 24,500 pounds (11,250 Kg) and 18,645 pounds (8,390 Kg) for the front and back axles respectively.

Load plan for High Weight Customer Order

Pallet Pos.	ID	WT	POS	SKUS
Pallet Pos. 1	F20	985	24.0	100014
	F14	1085	24.0	100026
	F1	336	24.0	537001
	F13	1085	24.0	100026
Pallet Pos. 2	F7	2130	72.0	100295
	F15	1085	72.0	100026
	F3	336	72.0	537001
	F2	336	72.0	537001
Pallet Pos. 3	F37	960	120.0	100012
	F19	1085	120.0	100026
	F36	960	120.0	100012
	F35	988	120.0	100013
Pallet Pos. 4	F32	988	168.0	100013
	F31	988	168.0	100013
	F30	988	168.0	100013
	F29	988	168.0	100013
Pallet Pos. 5	F28	988	216.0	100013
	F27	988	216.0	100013
	F26	985	216.0	100014
	F25	985	216.0	100014
Pallet Pos. 6	F24	985	264.0	100014
	F23	985	264.0	100014
	F22	985	264.0	100014
	F21	985	264.0	100014
Pallet Pos. 7	F16	1085	312.0	100026
	F8	2130	312.0	100295
	F5	336	312.0	537001
	F4	336	312.0	537001
Pallet Pos. 8	F34	988	408.0	100013
	F6	1982	408.0	100921
	F33	988	408.0	100013
Pallet Pos. 9	F18	1085	360.0	100026
	F17	1085	360.0	100026
	M2	975	360.0	100012 100014 100104
Pallet Pos. 10	F12	2033	456.0	100104
	M1	814	456.0	100026
Pallet Pos. 11	F11	2033	504.0	100104
Pallet Pos. 12	F10	2033	552.0	100104
Pallet Pos. 13	F9	2033	600.0	100104

Figure 40. The load plan generated by SLSH for the high weight customer order shown in Figure 38. The first pallet listed for each pallet position is placed on the bottom left-hand side, looking forward, of the pallet position. The second pallet is on the bottom right-hand side. The third pallet is on the top, left-hand side of the pallet group and the fourth pallet is on the top right-hand side. Pallet weight and distance from the front of the trailer to the geometric center of the pallet are also shown.

C. Defense Logistics Agency Customer Order

An actual customer order from DLA is displayed in Figure 41. This order is carried on 24 pallets and weighs 29,343 pounds (13,204 Kg): Weight is the critical load factor. The same 53-foot truck described in the previous two sections is used to transport this load. The only compatibility restriction between FSNs is that liquids may only be stacked on top of other liquids.

The SLSH procedure creates the load plan shown in Figure 42 requiring less than 1 minute on a desktop PC. Axle weights are 20,055 pounds (9,025 Kg) and 9,288 pounds (4,179 Kg) for the front and back axles, respectively.

FSN	Description	Height	Weight	Cls	Quant.
11929173	Juice, Orange	36	1697	Liq	1
2729939	Cereal, Cornflakes	58	296	Dry	3
2523838	Crakers	60	3900	Dry	3
435352	Taco Shells, Corn	58	500	Dry	4
13896155	French-Salad Dres	50.5	1200	Liq	1
4831353	Macaroni	34.7	132	Dry	6
2220601	Chow-Mein #10	49.4	525	Dry	2
7823765	Chs Grated Parm.	51.2	2250	Dry	3
10594082	Soysauce	54	3266	Liq	1

Figure 41. A customer order from the Defense Logistic Agency. There are two classes of FSN listed: Liquid and Dry. The only compatibility restriction is that liquids may only be placed on top of other liquids.

	ID	WT	POS	FSN
Pallet Position 1	F14	132	24.0	4831353
	F15	132	24.0	4831353
	F16	132	24.0	4831353
	F17	132	24.0	4831353
Pallet Position 2	F1	296	72.0	02729939
	F23	3266	72.0	10594082
	F2	296	72.0	02729939
	F12	132	72.0	04831353
Pallet Position 3	F7	500	120.0	0435352
	F22	2250	120.0	7823765
	F8	500	120.0	0435352
	F19	525	120.0	2220601
Pallet Position 4	F3	296	168.0	2729939
	F9	500	168.0	0435352
	F13	132	168.0	4831353
	F10	500	168.0	0435352

	ID	WT	POS	FSN
Pallet Position 5	F11	1200	216.0	13896155
	F20	2250	216.0	07823765
	F18	525	216.0	02220601
Pallet Position 6	M1	1697	264.0	11929173
	F21	2250	264.0	07823765
Pallet Position 7	F4	3900	168.0	02523838
Pallet Position 8	F5	3900	312.0	02523838
Pallet Position 9	F6	3900	360.0	02523838

Figure 42. The load plan generated by the SLSH portion of PATL for the customer order contained in Figure 41.

VI. LITERATURE REVIEW

Literature concerning solution methods for pallet picking and truck loading can be separated into two categories: Optimization or heuristic. The optimization literature proposes optimization techniques to solve the pallet picking and truck loading problems while the heuristic literature proposes efficient informal methods.

A. Optimization Literature

1. A Mathematical View of Pallet Picking and Truck Loading

Because efficient patterns of rectangular containers have minimal wasted pallet area, and efficient load plans have minimal wasted floor area, mathematical models of pallet picking and truck loading suggest the general category of two-dimensional cutting stock and set packing problems (abbreviated as C&P in the following) [e.g., Dyckhoff, 1990]. The goal is to find two-dimensional patterns with minimal unused area [e.g., Schrage, 1991].

Mathematical models of truck loading attempt to place as many small rectangles (containers or pallets) as possible inside a larger containing rectangle (pallet or truck) [H. Carpenter and W. Dowsland, 1985]. The models and thus the solutions obtained using this approach may not recognize real-world requirements such as SKU compatibility. Mathematical models may add complexity without rendering much insight.

2. Problem Classification

Dyckhoff [1990] develops a "consistent and systematic approach for a comprehensive typology" based on the basic logical structure of the C&P. He differentiates the main characteristics of C&P based on the dimensions involved, method of assignment and the variety of large and small items available.

3. Mathematical Models

Many methods have been proposed to solve variations, usually specializations of the C&P problem. Ram [1992] provides a survey on the literature concerned with this topic.

The two dimensional C&P has received much attention. Gilmore and Gomory [1966] propose a method using dynamic programming to solve the C&P problem. Herz [1972] propose a recursive algorithm that improves on Gilmore and Gomory's approach by restricting the possible subproblems to an integral combination of the length or width of the boxes being packed. Christofides and Whitlock [1977] use a tree-search algorithm to solve two-dimensional cutting problems. Beasley [1985] proposes a Lagrangean relaxation based tree search algorithm for the two-dimensional problem. Dowsland [1987, 1990] presents a model using graph theory to solve the two-dimensional problem.

B. Heuristic Literature

1. A Complexity Argument for Heuristics

Cutting stock and set packing problems are reducible to the "bin packing problem" [e.g., Chvatal 1983 and Dyckhoff, 1990] which has been shown to be non-deterministic polynomial-complete (NP-complete) [e.g., Garey and Johnson, 1979]. This means that there are no known efficient algorithms resulting in an optimal solution [e.g. Bischoff and Marriot 1990, Bazaraa et. al. 1990 and Cormen et. al 1992]. NP-completeness suggests heuristic procedures for practical solutions to C&P, especially within reasonable time limits.

2. Problem Classification

Heuristic pallet picking and truck loading rely on decision rules: A decision rule defines what action to take based on problem variables. For example, if you have 47 or more pallets to load (problem variable) use a 53 foot truck (action). Several methods have been proposed for segmenting the pallet picking problem based on problem variables.

Hodgson [1982] segments the pallet picking problem into two groups: The manufacturer's and distributor's problems. The manufacturer's problem concerns loading a single SKU type onto a pallet. The distributor's problem concerns loading non-identical SKUs onto a pallet.

Bischoff and Marriot [1990] propose a method to compare efficiency between heuristic procedures for container loading. Container loading seeks to place small rectangular objects into a larger rectangular containers and thus is related to pallet picking and truck loading. Bischoff and Marriot use multiple problem variables to segment the container loading problem. One variable is the availability of shipping containers: Is all cargo shipped in a combination of containers, or is as much cargo as possible shipped in one container? Bischoff and Marriot further segment the container loading problem based on critical load factor. Lastly, they segment the container loading problem based on the cargo handling or fragility aspects of the load: Can all SKUs be loaded together, or do restrictions occur that limit the placement of cargo?

3. Loading Considerations

A common question concerning pallet picking and truck loading is: Are there characteristics that all "*good*" loads have in common?

Ram [1992] offers broad "consideration categories" critical for proper loading. His first consideration category is maintaining load integrity during transport. One measure of load integrity proposed by Carpenter and W. Dowsland [1985] is load stability. They discuss the importance of stability and offer methods to quantify it. Bischoff and Ratcliff [1995] argue that the distribution of load weight is critical to load integrity.

Ram's second consideration category is the efficiency of the palletization task. Bischoff and Ratcliff [1995] offer several measures of efficiency. SKUs should be grouped by type. For example, SKUs of the same size should be loaded near each other. Further, they state that some subsets of cargo may form a "functional entity" and thus should be shipped together. For example, the parts required to assemble a machine should be collocated. Lastly, the complexity of the loading arrangement must be considered. The more complex a loading pattern, the greater the time and effort required to load.

4. Heuristic Methods

Hodgson [1982] develops a two dimensional solution to the pallet picking problem using a combination of dynamic programming and heuristics.

George and Robinson [1980] develop a three-dimensional packing algorithm that builds vertical "walls" across the width of the container. Multiple box sizes are allowed. Gehring et. al [1990] propose another "wall" building heuristic that loads a container with non-identical boxes. Their method computes multiple feasible load plans from which the user selects the most suitable. George [1992] proposes a heuristic for solving the three-dimensional packing problem using a single box size. One common trait of these three-dimensional methods is that they rely on the container wall for load stability. While this may be acceptable for the container loading problem (i.e. truck loading) it is clearly not sufficient for the pallet loading problem without supporting walls. This shortcoming is addressed by a heuristic proposed by Bischoff et. al [1995] that builds layers of non-identical SKUs from the floor up. This approach does not rely on container walls for stability nor does it build columns of SKUs which are inherently unstable.

Cochard and Yost [1985] describe a modified cutting stock heuristic used by the US Air Force to generate feasible cargo loads. This heuristic model reduced load-planning man-hours by 90 percent and increased aircraft utilization by 10 percent. Anderson and Ortiz [1987] discuss a similar heuristic model used by the US Army for planning aircraft loads.

Garza et. al [1992] present a model that constructs loadplans for multiple SKUs carried in a single truck. The idea is simple and efficient. A customer order is fitted using a generic set of prearranged loadplans. The loadplan that offers the highest volume utilization is selected. This model does not address the problem of axle weight limits or product compatibility. The model resulted in a seventy-five percent savings in man-hours and a five percent higher truck utilization rate.

Haessler and Talbot [1990] present a complex heuristic procedure that develops three-dimensional loadplans of loose containers for trucks, tandem trucks and railcars. This model is of particular interest because if we view their loose containers as pallets, they address a generalization of our problem. The model assumes only one size of truck is available for a load. Their heuristic is completed in seven steps. In the first step the number of stack positions in the vehicle is estimated.

In Haessler and Talbot's second step the number of pallet stacks is estimated. A pallet stack is a group of full pallets and full layers placed on top of each other forming a column. Loose cases are left to be hand loaded. (The heuristic presented in this thesis computes pallet groups in essentially the same manner.)

In step three the customer order is adjusted up or down based on the number of available pallet positions and the number of pallet stacks. For instance, if the estimated number of pallet stacks exceeds the estimated number of pallet positions, the customer order is reduced. Conversely, if there are more pallet positions than pallet stacks the customer order is increased. The Haessler and Talbot heuristic treats customer order quantities as an endogenous variable. (The heuristic presented in this thesis assumes the customer order to be fixed: The order quantities may not be adjusted to improve vehicle utilization.)

In step four pallet stacks are formed using two primary considerations: Heavy SKUs should be on the bottom of the stack, and all SKUs in the stack should have similar base dimensions (length and width). This heuristic assumes that all SKUs are compatible, an unreasonable relaxation of the general truck loading problem. (The heuristic presented in this thesis ensures SKU compatibility when picking mixed layer pallets and truck loading.)

In step five pallet stacks are arranged in the truck in two stages. In the first stage, the pallet stacks formed in step four are ordered based on customer, drop-off sequence and SKU similarities. It is noteworthy that this heuristic addresses multiple customer orders, multiple destinations, stacks of more than two containers, and pallet dimensions other than a standard 40x48 inches. (The heuristic presented in this thesis does not allow for these possibilities.)

Pallet stacks are arranged in the truck by Haessler and Talbot to maximize cube utilization. This method may not be adequate for high-density loads. (The heuristic presented in this thesis is capable of alternate load planning for either low-density or high-density loads.)

In the second stage of the fifth step pallet stacks are arranged in the truck (using loading patterns similar to those used in this thesis). The load is balanced about the lateral axis by alternating the heavy pallets from left to right along the longitudinal axis of the truck. (This method is also used in the heuristic presented in this thesis.)

The Haessler and Talbot heuristic assumes that load weight is equally distributed and thus each axle will bear exactly one half of total load weight. (The heuristic presented in this thesis computes axle weights directly: The location and weight of each pallet is used to compute axle weights.)

Step six is a checking routine: It determines if pallet stacks can be added to the load or if the load must be reduced. In step seven gaps are hand loaded with loose cases.

Haessler and Talbot report that "very favorable results" were accomplished with this heuristic.

The methods presented here generalize the work of Haessler and Talbot by treating customer order quantities as fixed, computing and honoring axle weights, and considering SKU compatibility in building and stacking pallets.

VII. CONCLUSION

A. Summary

Efficient pallet picking and truck loading is an economic fundamental. Improperly loaded pallets or trucks may result in poor cube utilization or damage to goods during transport.

The optimization models suggested by the pallet picking and truck loading problem are reducible to the "bin packing problem" which is known to be NP complete: No known efficient algorithms exist that result in an optimal solution. NP-completeness suggests heuristic procedures for practical solutions to C&P, especially within reasonable time limits.

A heuristic procedure to aggregate containers onto wooden pallets and plan the loading of the pallets into trucks has been introduced. The heuristic require less than 2.5 minutes on a personal computer to determine load plans that enforce SKU compatibility restrictions and ensure axle weight limitations are met.

B. Recommendations For Further Research

The heuristic presented in this thesis considers only 40x48 inch pallets. This is an important simplifying assumption. Many items are shipped on odd sized pallets, crates, slip sheets, etc., or have pallet over-hang or under-hang that limit the usefulness of this heuristic. A heuristic that could address multiple sizes of loaded units would be most useful.

This heuristic does not handle SKUs packaged in other than rectangular containers. Although some shapes, such as cylindrical drums, may be viewed as occupying their circumscribing rectangular footprint, an improvement to the pallet picking portion of this heuristic that would allow the inclusion of non-rectangular containers would be an important refinement. We note that a good deal of military cargo is odd-sized.

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